Microwave Line-of-Sight Transmission Engineering

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Abstract

This article describes microwave line-of-sight radio, one of several transmission media in modern telecommunications networks. The topic is approached from two standpoints: the physics of microwave propagation and project implementation. Inasmuch as a microwave link is a circuit between terminals separated by a sizable distance, it can be considered a type of transmission line; but unlike copper or fiber optic cables, terrestrial microwave signals are propagated through the lower atmosphere. Thus they are sensitive to terrain, atmospheric, and climatic conditions adverse to error-free reception. An important part of microwave engineering is to account for these conditions and provide technical corrections. On the project side, constructing a microwave relay system is an interdisciplinary activity; besides microwave path and equipment engineering, several other engineering disciplines are required: civil engineering for site preparation and access roads; structural engineering for towers, foundations, supports, and buildings; and electrical engineering for power, lighting, and grounding.

INTRODUCTION

Telecommunications transmission facilities are the physical means of communicating large amounts of information over distance. Without exception, communication signals (speech, images, video, or computer data) are electromagnetic waves traveling along transmission lines such as those in Fig. 1. For a given route, the type of transmission line selected depends on the topography, the amount of information to carry, and the cost. Even though fiber optic cable carries more information with higher reliability than does any other transmission medium, for a long distance over remote or rugged terrain, a microwave relay system is sometimes the better economic alternative.

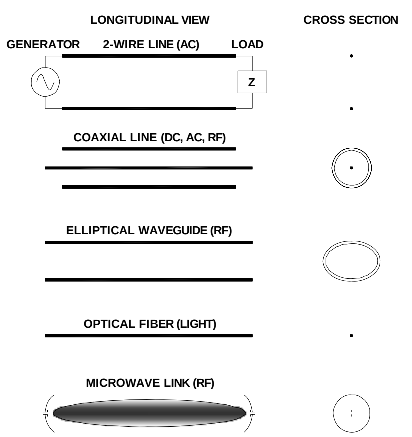

Fig. 1. Types of communication transmission lines.

A cable or waveguide serves to contain the electromagnetic field of a signal as it propagates so that most of the power from the transmitter is guided to the receiver and not wasted in unwanted directions. By contrast, radio signals are transmitted through the air as unguided waves, which spread over distance, so that their power density per unit area is diminished at a receiving antenna. Nonetheless a parabolic antenna can concentrate a microwave signal in a chosen direction, just as a parabolic mirror can focus light to a spot beam. Microwave beams travel over roughly the distance from here to the horizon, which accounts for the term *microwave line-of-sight*. As mentioned above, a series of microwave relay stations, one after another, is sometimes more economical than a cable system between two terminal points. Which transmission medium to use is one of the first questions the engineer must answer when given the requirement to design a communication system. In this article, it is assumed that a determination is made in favor of microwave, whence the practical aspects are considered of designing and implementing that particular type of communication system.

MICROWAVE PROPAGATION

Basic Principles. *Microwave* refers to wavelengths of the electromagnetic spectrum between one meter and one centimeter. Microwave propagation engineering has a physical part and a statistical part. For unbounded propagation through vacuum, far from material objects, engineering design can approach exact results based on the laws of electrodynamics. The *free space loss* for a signal is due to spreading of the electromagnetic wave with increasing distance from the transmitting antenna. As microwave energy spreads over an ever expanding spherical surface, its power flow per unit area decreases. The signal attenuation over distance from the source also depends on the frequency; the higher the frequency, the greater the attenuation. Therefore, given the frequency, the free space loss between two fixed points is constant regardless of other details of the path.

Transmission formulas add in the gains and losses of radios, transmission lines, antennas, and path details of a hop. The transmitter power minus waveguide losses plus its antenna gain sets the baseline for the free space loss and additional propagation losses along the path (Fig. 2). The microwave transmission engineer analyzes a propagation path as far as possible in terms of the reflection, diffraction, and refraction of electromagnetic waves. Absorption of electromagnetic energy by atmospheric gases is also significant in certain parts of the spectrum. Furthermore, the relative importance of these mechanisms, in contributing additional losses over a particular path, depends on weather and the terrain.

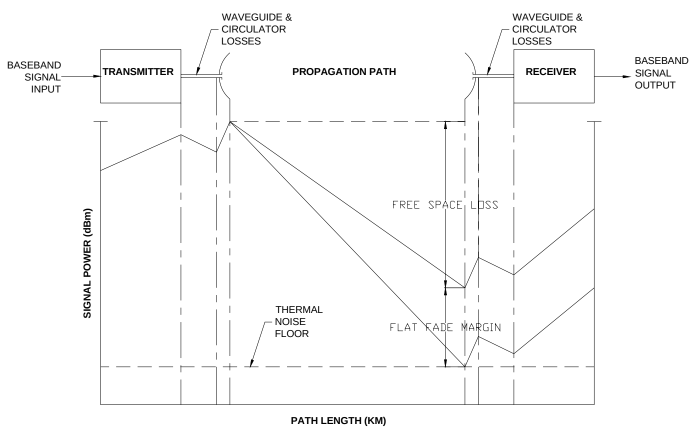

Fig. 2. Microwave path gains and losses.

That brings up the statistical part. For stations on the ground, transmitting through the lower atmosphere, an analysis of propagation is complicated by uncontrolled variables associated with climate, weather and the path terrain. Signals are said to undergo *fading*, which refers to the fact that time-varying atmospheric processes influence the mechanisms of reflection, refraction, and diffraction, separately or in combination, so as to cause signal losses at a receiving antenna in addition to the free space loss. At any given moment, the atmospheric conditions that cause fading cannot be known exactly; therefore we cannot be certain of how a received signal will vary in time. The alternative is to observe the time variation of received signals for many paths and for a variety of transmission conditions. Statistical methods can then be applied to the accumulated observations to predict the occurrence and severity of fading.

Since microwave propagation is governed by the principles of reflection, refraction, and diffraction, it is useful to have two simplified views of a microwave signal in order to describe which principles are dominant for a given path. The first view is that of the refraction and reflection of a radio wave (Fig. 3). A straight line with an arrow in the direction of propagation, or *ray,* represents a direct microwave beam between antennas. Over a long path, a beam can undergo discernible bending, or *refraction*, in the vertical plane. Refraction of a beam is caused by a gradual change in the index of refraction versus height in the lower atmosphere. The amount and direction of bending depend on the refractive gradient of the atmosphere and the frequency of the microwave beam. The refractive gradient changes slowly depending on the time of day, season, geography, and climate; and the beam bending changes accordingly. Another effect of refraction is *multipath fading*, which is the result of nonlinear phase shifts to the frequency components of a transmitted signal. This phenomenon is discussed in more detail in the next section.

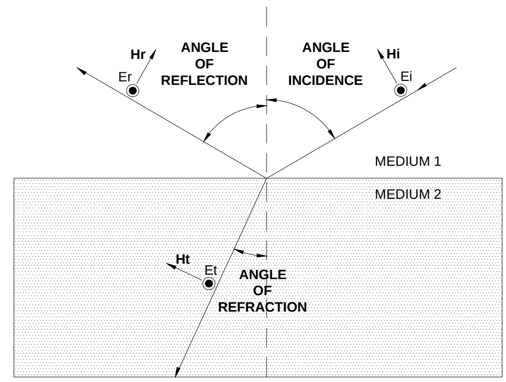

Fig. 3. Principles of reflection and refraction.

Rays are also used to represent reflections by the ground or by boundaries between atmospheric layers. Reflection of a microwave beam is classified as *specular* or *diffuse* depending on whether the terrain is smooth or rough. In specular reflection, an incident ray is strongly reflected, and according to Snell's law, the angles of incident and reflected rays from the vertical are equal. Ground reflections near the mid-point of a path are also a cause of multipath fading at a receiving antenna due to combining of the direct and out of phase reflected rays canceling the signal. In diffuse reflection, rough terrain scatters an incident ray in random directions, so that the scattered rays do not contribute to multipath fading.

Although the direct beam bends slightly, it is often drawn as a straight line on profile charts. The actual curvature of the beam is transferred to the terrain profile of the path, with the constraint of maintaining, point for point, the actual height of the beam above the ground. A measure of bending, known as the *effective earth's radius factor*, or *K factor,* relates atmospheric refraction to the average value of the earth's radius.

Physically, a microwave beam has a cross-sectional width of which the direct ray is the axis. The measure of beamwidth is the *first Fresnel zone*, which is an ellipsoid containing most of the signal power that reaches the receiving antenna. For a fixed path, the first Fresnel zone becomes narrower with increasing frequency and larger antennas. *Path profiles* show the clearance of a microwave beam and its Fresnel zones above the ground with K factor as the parameter. In the vertical plane, the first Fresnel zone defines the ellipsoidal boundary inside of which reflected rays do not interfere with the direct ray at the receiving antenna. The outside surface of the first Fresnel zone is where terrain or obstructions begin to cause diffraction loss.

A diffracted beam follows a path that is neither due to reflection nor refraction, but is explained by Huygens' Principle governing the bending of electromagnetic waves around obstructions. Diffraction of a microwave signal is represented as spherical surfaces, or *wavefronts*, in proximity to a partially blocking obstruction (Fig. 4). The proximity of smooth terrain, or of a sharp obstruction, to the direct ray of a signal creates a shadow zone in which diffracted signal energy is lost. Diffraction over a microwave path is sometimes due to an apparent earth bulge into the line-of-sight of the signal. However, the formation of the apparent earth bulge is actually caused by refraction of the microwave beam so as to graze the terrain along the path.

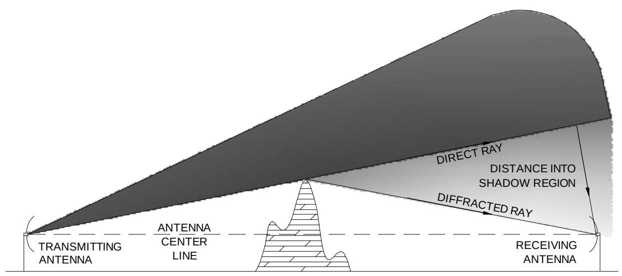

Fig. 4. Diffraction over knife-edge obstruction.

Multipath Fading. During the era of analog FDM-FM microwave radios, *flat fading* (also called *power fading*) was the most serious transmission impairment. The word "flat" means that all frequencies of the signal passband are attenuated equally. Sufficient power margin was designed into a link to handle flat fades of 30-40 dB below the unfaded free space loss at a receiver.

When digital microwave radios were introduced, system designers discovered that, for signals well within an acceptable flat fading margin, a phenomenon called *multipath fading* frequently causes the *bit error ratio* (BER) threshold to be exceeded. Under multipath conditions, the receiver sees a weighted sum of time-shifted replicas, or echoes, of the transmitted signal. The echoes are caused when the signal is reflected from multiple atmospheric layers or the ground; and they follow slightly different path lengths to the receiving antenna. The vector summation of echoes with the direct ray can either add to or cancel the received signal strength depending on the atmospheric conditions at the moment.

High-capacity digital radios transmit bandpass signals of 30, 40, or 50 MHz bandwidths depending on the operating frequency band. For such large bandwidths the resultant signal cancellation due to multiple reflected rays, is *frequency selective*. The bandpass signal's frequency components undergo nonlinear phase shifts and some frequency components also undergo amplitude attenuation, thus distorting the envelope of the propagated signal. The effect on the demodulated baseband signal is dispersion of pulse energy; that is, each bit overlaps with the previous and succeeding bits, blurring the logical levels at the sampling times, and increasing the likelihood of decision error. This is called *inter-symbol interference* (ISI), and it is directly correlated to increases in BER. Performance degradation due to multipath fading increases rapidly for microwave paths longer than 25 miles.

To evaluate the performance of digital radios, it is necessary to model the effects of the atmosphere on digital signals as they pass through the propagation channel. During normal propagation conditions (i.e., simple flat fading), digital transmission is nearly error-free. The modeling problem is to represent the effect of propagation defects, or anomalous propagation conditions, which are present on the path for a small fraction of time during the year. A *multipath fading channel model* is a statistical model for estimating the fraction of time that the propagation conditions on a path will be too severe for a radio to meet an acceptable performance criterion in terms of BER for a defined interval.

There are two types of fading channel models: *atmospheric* models are based on *ray tracing* techniques, which depend on measurements or assumptions about the height gradient of the index of refraction. The other type of model is the *channel* model, which fits a formula, called a *model function*, to measured propagation channel responses over the digital signal's passband by suitable choices of the model function's parameters. Particular characteristics of a path, such as climate, terrain elevations, and terrain roughness determine the values of the model parameters. The channel model is a purely statistical approach to representing propagation effects on the signal. Since channel models lend themselves readily to computer simulation, they are commonly used for designing and evaluating digital radios.

If the time variation of the propagation channel response is too rapid, the dynamic response of receiver circuits for carrier recovery, timing recovery, and equalization may start to exhibit *hysteresis*. Hysteresis is when the dynamic response of radio circuits is related not only to the current state of the propagation channel, but also to its past states. The combination of dynamic channel behavior and receiver hysteresis can affect system performance, but is harder to characterize in a model than are static propagation anomalies. Ultimately, all propagation models have the common need to relate model parameters to root physical causes: path parameters, local terrain conditions, and local climate.

MICROWAVE PATH ENGINEERING

Preliminary Planning. A microwave network's size and setup depend on transmission system planning: traffic analysis, provisioning, and network topology. *Traffic* refers to the voice phone calls and computer sessions offered to the switches, multiplexers, and transmission equipment of a telecommunications network. To design a new network, traffic engineers must obtain numbers of users, their geographic distribution, and their calling behavior, either through direct surveys or reliable statistical data.

This information is necessary to *provision,* or size and configure, the switch, multiplexer, and transmission equipment for a specified performance level, or *grade of service.* Without an accurate estimate of the traffic of a service area, it would be difficult to design a transmission system that maintains a required grade of service economically. In other words, lacking sufficient information, the tendency is to build a larger system than is necessary.

The network *topology*, or layout, is the product of an analysis to determine the optimal connections between switching centers and locations where traffic would be added or dropped from the aggregate streams of the transmission system. An optimal topology has sufficient direct and alternate routes to carry the offered traffic at all times.

From the microwave engineer's standpoint, a network layout shows where microwave repeater stations might be needed; thus he begins to define the line-of-sight paths of the network. To keep the BER to an acceptable level most of the time, the ambient noise and interference levels at each end of a path must not exceed certain values. Likewise, outages caused by propagation losses must be brief in duration. The prescribed BER, propagation outage, and time percentages are the *performance objectives*. They are derived from the system requirements for the overall network.

Once the major nodes of the network are known, maps, imagery, and the region's topography are studied to identify possible microwave terminal and relay locations. Features to look for are site accessibility on existing roads throughout the year, and availability of commercial electric power. Since the paths will be line-of-sight, their maximum length should be 25 to 30 miles, and considerably shorter if the microwave bands above 10 GHz are to be used. Nearby airports and other microwave systems should be noted on maps and aerial photos. Not only are they potential sources of interference, but the path design must preclude causing interference to these existing services as well. The process of identifying candidate paths is continued until the entire network can be spanned, and then the prospective sites and their connections are added to the network diagram to create a microwave route map (Fig. 5).

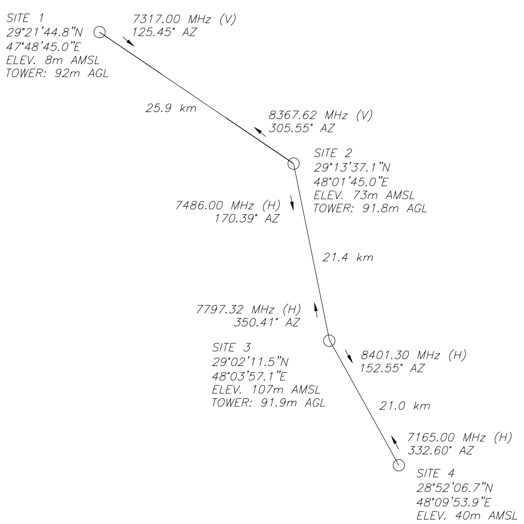

Fig. 5. Microwave route map and frequency plan.

Path Profiles and Calculations. The path design problem is to determine which values of equipment parameters meet link and network performance objectives at an economic cost. The primary equipment parameters are transmitter power, receiver sensitivity, and antenna height and gain. The design solution is arrived at iteratively by changing parameters, then noting the effect on path performance. To facilitate an accounting of parameter changes, path calculation sheets are used which list data pertinent to link description, equipment losses and gains, and fading effects in a spreadsheet.

The basic method is to check whether a choice of antenna size and height, for given values of transmitter power and receiver sensitivity, results in a sufficient fade margin for a received signal to remain above a threshold level after losses due to the distance, terrain, obstructions, reflections, and other atmospheric effects. In general, there is not a unique solution to the path design problem, and cost is usually the deciding factor. The end result of the design is a microwave installation drawing set and bill of materials for radios, towers, transmission lines, antennas, materials, and their arrangement into a system that will satisfy the stated performance objectives (Fig. 6).

To ensure satisfactory BER performance over a transmission link, only the direct ray and its first Fresnel zone should propagate along the path between the antennas. Ground-reflected rays should be blocked by intervening terrain features, or scattered by rough terrain so as not to cause multipath fading at the receiving antenna. Sharp obstructions or long stretches of smooth earth should not protrude too near the direct ray in order to prevent signal loss from diffraction. Ideally, the air in the vicinity of the path would be well-mixed and stable most of the time so that the reflective boundaries of a stratified atmosphere do not form. Under such conditions, the amplitude of the microwave signal is steady at the receiving antenna and the signal output from the receiver is an error-free reproduction of the signal driving the transmitter at the distant end. The transmission loss for such a propagation path is close to the free space loss.

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DRAWING NO.	SHT(S)	TITLE	REMARKS
EK101TC-DI80001	1	DRAWING INDEX	THIS SHEET
EK101TC-SY80001	4	SYSTEM DIAGRAMS	
EK101TC-SY80002	1	SIGNAL FLOW DIAGRAM	
EK101TC-VM80001	4	VICINITY MAP	
EK101TC-VM80002	1	ROUTE MAP	
EK101TC-SP80001	1	SITE PLAN	
EK101TC-FP80001	1	FLOOR PLANS	
EK101TC-RE80001	1	RACK ELEVATIONS	
EK101TC-GS80001	2	GROUNDING (TBD)	
EK101TC-AS80001	1	ALARMS (TBD)	
EK101TC-PD80001	2	POWER DIAGRAMS	
EK101TC-AT80001	1	ANTENNA DETAILS	
EK101TC-ID80001	2	INTERCONNECTION DIAGRAM	
EK101TC-RP80001	1	RADIATION AND PATH PROFILES	
STD-MX-0138	6	8 GHz WAVEGUIDE SYSTEMS INSTALLATION DETAILS	
STD-MX-XXXX	4	CHAIN LINK FENCE INSTALLATION DETAILS	

Fig. 6. Engineering installation drawings.

Usually the choice of station locations is limited, and the desirable conditions above often do not exist. Then, the microwave engineer uses several techniques to counteract fading and interference. For example, diversity techniques are commonly used to counter fading over a long path (Fig. 7). *Space diversity* and, less often, *frequency diversity* are used to obtain a de-correlated replica of the transmitted signal, either at a second point in space (using a second antenna) or on a second frequency at the same antenna. The proper vertical antenna spacing or separation of two frequencies is chosen so that fading occurs at just one antenna or on one frequency at a given time. Thus if the signal fades at the main receiving antenna, the replica signal at the diversity antenna will likely be strong. Similarly, if the signal fades on the main frequency, the replica signal on the second frequency will likely be strong.

In some climatic regions of the world, however, anomalous propagation is known to occur in which downward refractive bending of a microwave signal is so strong that the signal literally falls short of the receiving antenna. In such cases, conventional design techniques cannot overcome the impairment; this is called *blackout fading*. Known areas of blackout fading should be avoided if possible.

Based on the route map, the microwave engineer creates path profiles of all the candidate paths. The required tower heights, antenna gains, transmitter power, and receiver sensitivity for a given path depend, in part, on how the microwave beam bends throughout the day, and by season. A terrain profile is a sectional cut in the vertical plane through the earth's surface along the path; it is a plot of terrain elevation above mean sea level versus distance from one station to the other. The curvature of a terrain profile depends on the value of K factor. Since a path undergoes a range of curvature on a daily cycle, profiles of the terrain are shown for sample K factor values corresponding to that range. Nowadays computer programs are used to draw path profiles (Fig. 8), and usually it is most convenient to plot the rays representing wave components as straight lines and show a separate terrain profile for each value of K factor. The curved line under each ray is a Fresnel zone boundary. The first plot shows that there is more than enough clearance for the first Fresnel zone F1 at K=1.25, while the second plot is the worst case of 30% F1 clearance at K=2/3. The hatched terrain profile in each plot is for the reference value of K=∞.

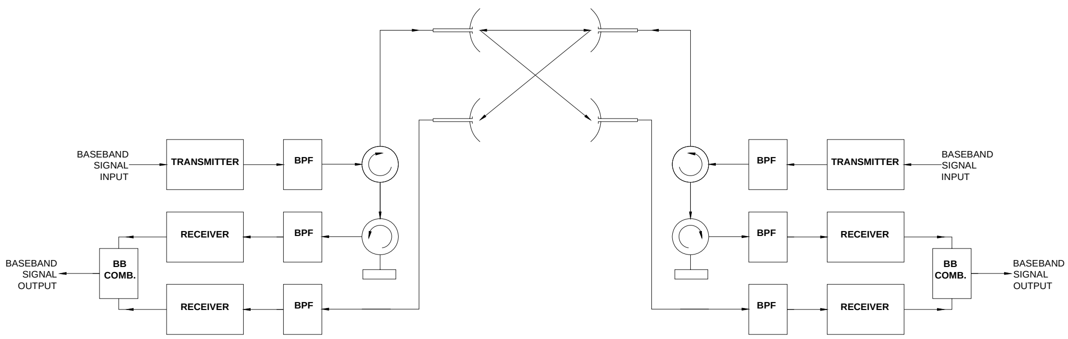

Fig. 7. Concept of space diversity.

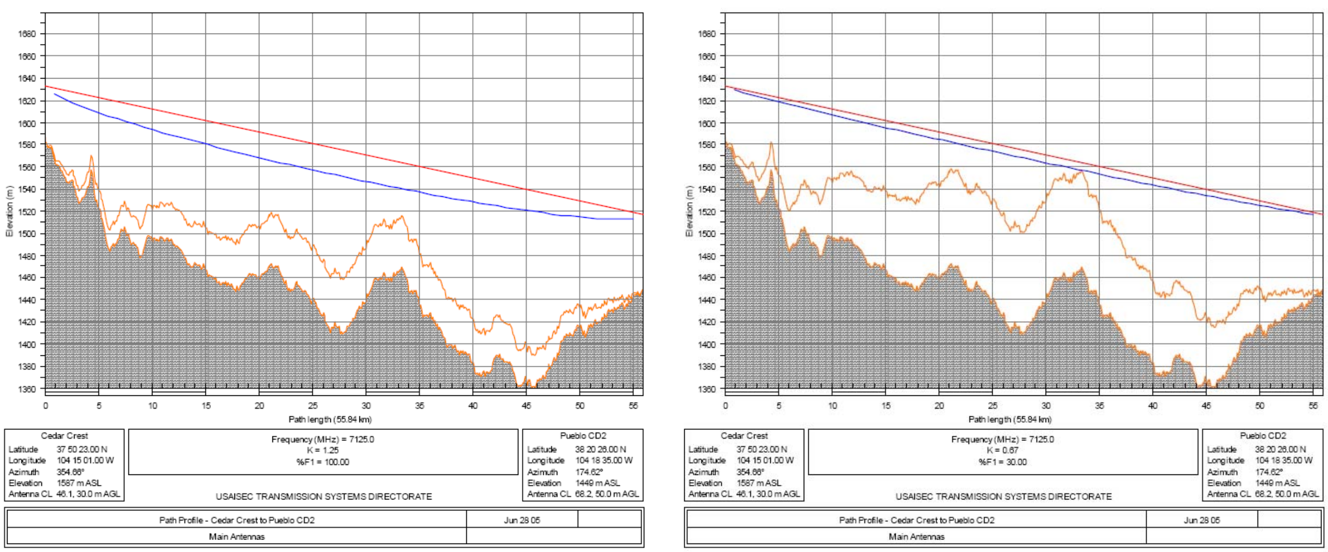

Fig. 8. Path profile diagrams for K=1.25 and 0.67 (hatched profiles are for K=∞).

<u>Outages.</u> An outage event occurs when the BER exceeds a specified threshold for less than ten consecutive seconds; longer than that, the link is said to be *unavailable*. The distinction arises from the fact that digital trunks lose framing when high BER persists longer than the defined outage duration. *Outage time* is the accumulated time for all outage events in a given period; for example, a year. A reliable outage calculation method accounts for both noise (flat fading) and inter-symbol interference due to multipath fading. It also includes the effects of both external interference and equipment imperfections. Finally, it is general enough to

account for both space diversity and dual polarization operation.

Substantial database resources must be at hand to create the initial network layout and path profiles, since the engineer will usually not have conducted a field survey up to this point. In the present state of the art, radio propagation and geographic information systems (GIS) software programs are available which use maps, aerial imagery, and terrain elevation data sets (all of them in digital formats) to create terrain profiles, visual topographic displays, and reports, thereby enabling a first-cut propagation analysis of the candidate paths. By comparing the initial path profiles, the engineer can reduce the candidates to a manageable number for a field survey. Operational requirements, system capacity, expansion potential, reliability, and costs are the most important considerations in the selection of paths to serve the fixed sites of the network.

Field Survey. The propagation variations of each path are determined by its terrain, obstructions, and atmospheric conditions. One purpose of a microwave field survey is to collect accurate data on locations and elevations of critical terrain points along a path, heights of obstructions, and meteorological data in the vicinity of a path. Accuracy is essential in order to meet the performance objectives of a microwave transmission system. Uncertainty in locations and elevations forces the engineer to be conservative about the clearance required for the line-of-sight between antennas. Consequently, he may specify higher towers and larger antennas than are necessary, which increases the total system cost. Furthermore, if the antennas are too high, link performance is more likely to be degraded due to greater exposure to interference and ground reflections. Although preliminary path profiles permit a comparison of alternative paths, terrain elevation databases and topographic maps are less accurate in many cases than is required for the final path design. Therefore, it is important to verify or make necessary corrections during a field survey.

To obtain accurate data, the engineer makes field measurements using the proper instruments and procedures for their use. For example, the coordinates of an existing tower are easy to survey to ±0.1 arc-second of latitude and longitude with available GPS receivers, especially in areas where Differential GPS (DGPS) is in effect. The conventional optical transit is used to measure the heights of obstructions. As for a tower's base elevation above mean sea level, or its height above ground, or an antenna's height and diameter, accurate values of these quantities are also important to a valid path design. They cannot be known just by looking at the tower and antenna; rather they must be measured by suitable land and construction surveying techniques. Precision barometric altimeters are used to meet the required accuracy for ground elevation measurements. Similarly, when *walking* a long path, the surveyor has the practical problem of knowing exactly where the path is, and how far off the path he is. A line-of-sight path should be verified, when feasible, by using signaling mirrors, a searchlight, or a balloon on a reflective tether.

These and other details constitute the ground truth of a microwave path. After they are measured, elevation corrections and vertical obstruction heights are entered in the digital terrain elevation model; frequencies are entered in the channel databases of the propagation software. Then the preliminary analyses are repeated using the revised databases, and compared to the preliminary propagation analysis to check for significant differences in performance and reliability.

The other major purpose of a microwave field survey is to describe completely all prospective sites. Sketches are made of both existing and green field sites showing structures, property lines, access roads, and proposed locations of new towers and equipment housings. These locations should be marked on the ground with monuments if possible. Sketches are accompanied by written directions for finding the sites, and notes on soil type, vegetation, drainage, etc. For each site, it is also important to note owner and local contact information, power availability, and meteorological data.

Interference and Frequency Coordination. Radio communication has traditionally been based on dividing the frequency spectrum into channels for multiple users. To accommodate as many users as possible, the bandwidth of each channel must be held to defined limits. Communication engineers have invented clever ways to transmit ever more bits per cycle of RF bandwidth; these techniques are known as *multi-level modulation* in which multiple bits are represented by each modulation state.

In electrical communications, there is a drawback for every benefit, and when more bits are modulated onto the same bandwidth, more transmitter power must be used to transmit those bits over the link at the same BER performance. A practical consequence of higher transmitter power is more energy radiated in undesired directions which causes more interference. Therefore, regulatory agencies, such as the FCC, place limits on the total power that each licensed transmitter can transmit [10].

Given the fixed microwave channel bandwidths, today's optical data rates have probably already outstripped microwave designers' ability to keep up, despite a strong need for radio-based transmission systems. The emerging answer is to move to the next higher region of the radio spectrum, millimeter-waves, where bandwidth is plentiful and many point-to-point links in a small geographic area can use the same great swath of spectrum without interfering with each other [11].

The effect of interference on microwave systems depends on the location of the new system relative to existing systems and their operating frequencies. If the power of an interfering signal is above a defined threshold compared to the desired signal (in other words, the C/I is below its defined threshold), a receiver does not operate correctly and errors in the received bit stream increase. Existing transmitters may cause intolerable interference to the new system, or vice versa. Aeronautical charts show the locations of existing microwave towers, and provide a check on database information. By locating owners, coordinates, and channels on aeronautical charts, route maps of other existing systems, and their antenna azimuths, can be determined. This is the information needed for a preliminary interference analysis.

During preliminary planning, assumptions are made as to which frequency band to use. Then, during the field survey, the local frequency manager is contacted to confirm that channel frequencies in the desired band are available for the new network. The survey engineer verifies the existing systems in the area in terms of owners, coordinates, channels, equipment, and routes. If the choice of frequencies is limited, and the likelihood of interference is significant, a spectrum monitoring study should be done to quantify the amount of interference at a site. A spectrum analyzer and monitoring antenna are set up at the site, and programmed according to a schedule to log the power of spectral components in a frequency band centered on a candidate channel frequency.

EQUIPMENT AND SITE ENGINEERING

Microwave Equipment Elements. The FCC's chapter on frequency assignments for the fixed microwave services lists 41 bands ranging from 928 MHz to 42.5 GHz [10]. Antennas, RF transmission lines, microwave combining and dividing components, and radios are the elements of microwave systems common to all of these bands, but their characteristics vary greatly over this range. The following paragraphs describe briefly these building blocks and their functions in system planning.

Antennas. The main types of antennas for microwave line-of-sight communications are *parabolics* and *horn-reflectors*. Parabolic antennas are available for all microwave radio bands, but their sizes and characteristics over that range vary greatly. Some are designed for low-capacity systems, such as grid antennas, others for high-gain and high-capacity, such as a 12' solid parabolic with shield and radome. Some parabolics can be specified to connect to coaxial transmission lines, and others to waveguide. In most cases parabolic antennas are used for single RF channel links. The exception to this rule is the 4-port multiband antenna which operates in two bands simultaneously with both polarizations for each band. Multiband antennas can be used for frequency diversity for a single channel or run two independent channels simultaneously.

In the technique of *dual-polarization frequency reuse*, two radios place independent baseband signals on the vertical and horizontal polarizations of the same carrier frequency, doubling the capacity of each frequency channel. Fig. 9 shows how this is a relatively efficient channel arrangement, but to be workable, it relies on a high level of *cross-polarization discrimination* (XPD) of parabolic antennas that are specially designed for this scheme. As a signal is propagated, it may undergo some de-polarization, i.e., a rotation of the electric field vector out of the vertical or horizontal plane, so that a component of one polarization is projected into the orthogonal polarization.

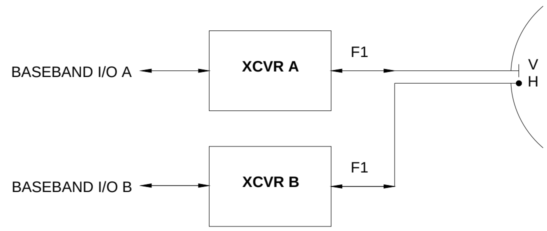

Figure 9. Dual polarization frequency reuse.

Horn-reflectors are large wideband antenna systems that are intended for use on links with multiple parallel RF channels. The radiation pattern of a horn-reflector is tightly controlled, and this allows it to be used at junction stations without causing interference on the same link or to other links.

For both antenna types, the performance characteristics are gain (referenced to an isotropic antenna), the half-power beamwidth, attenuation of side lobes, and the reflection factor.

RF Transmission Lines. The two main classes of RF transmission lines are coaxial cable and waveguide. Within each class there are many sub-types such as air dielectric coax or foam-filled coax, or circular, rectangular, or elliptical waveguide.

The two conductors of a coaxial transmission line are the center conductor and the outer circular conductor that encloses the center conductor (Fig. 1). This construction prevents loss of signal power, shields the signal against noise, and is easy to install. The use of coaxial cables in microwave work is limited to frequency bands below about 3 GHz.

For higher microwave frequencies, signal losses in coaxial cables become excessive, and it is advantageous to use waveguide as a transmission line. Waveguide has lower attenuation and greater power handling capability than coax, but is harder to install. If a dual-band or dual polarization antenna is used, two transmission lines must be connected to the antenna. A single antenna which is dual-band and dual-polarization has ports for four lines.

Combiners and Dividers. Microwave combiners and dividers are passive devices that enable several transmitters and several receivers to be connected to a single antenna, or two antennas to be combined into a single receiver. Some of the various configurations of circuit elements which act as combiners or dividers are circulator networks, bridge networks, branching networks, and polarization filters.

Radios. Since the advent of digital radios, the key areas for technology development continue to be: (1) high-level modulation for greater transmission capacity and spectrum efficiency, in bits/second/hertz; (2) predistortion and adaptive equalization to compensate for multipath fading; (3) dual-polarization, also for higher spectrum efficiency by doubling route capacity; (4) one-frequency repeating, another spectrum efficiency technique, which uses high performance antennas and transmitter power control to enable co-frequency transmission and reception on the same link; (5) high-density branching which uses interference canceling techniques to enable a wide variety of radio systems to co-exist at each network node; (6) higher frequency bands in the millimeter-wave and in the optical spectrum ranges for greater capacity; and (7) route diversity that switches adaptively to alternate hops and increases availability, particularly for the higher frequency bands.

For high-level modulation (64-QAM and higher), co-channel dual-polarization operation requires digital radios to contain a cross-polarization interference canceller (XPIC), which counteracts the tendency of a signal on one polarization to interfere with the signal on the orthogonal polarization, and vice versa.

Most improvements in digital microwave radio systems fall into two categories: (1) increasing transmission reliability, and (2) more efficient us of the available radio spectrum.

Given the susceptibility of digital signals to selective fading, and the need to create high-level modulations for spectral efficiency, the *adaptive equalizer* is an essential part of digital microwave radios.

The receiver function is the most fundamental communication task. To demodulate a signal, a digital radio must synchronize a local oscillator, in frequency and phase, to a received carrier, extract symbol timing, and estimate the values of received data symbols. For the small fraction of time that a link is affected by multipath fading, these receiver operations may be drastically impaired unless adaptive techniques are used. Therefore, adaptive functions (channel equalization, carrier and timing recovery, diversity, and cross-polarization interference cancellation) are included in addition to customary receiver function blocks such as fixed filters, amplifiers, and down-converters. Over time, it has been found that there is significant interaction between all of these adaptive functions, thus their optimal combination for countering severe fading continues to be an area of intense design effort.

Site Requirements. Equipment block diagrams are the means of summarizing equipment requirements at each site and defining their functional interrelationships. Block diagrams are also used to record major system parameters such as transmit and receive frequencies, transmitter power, waveguide lengths, antenna sizes and polarizations, etc. Individual equipment blocks should be depicted and uniquely identified so that no equipment will be overlooked. Equipment block diagrams provide a systematic basis for developing bills of materials. Fig. 10 is an equipment block diagram of a typical microwave terminal site.

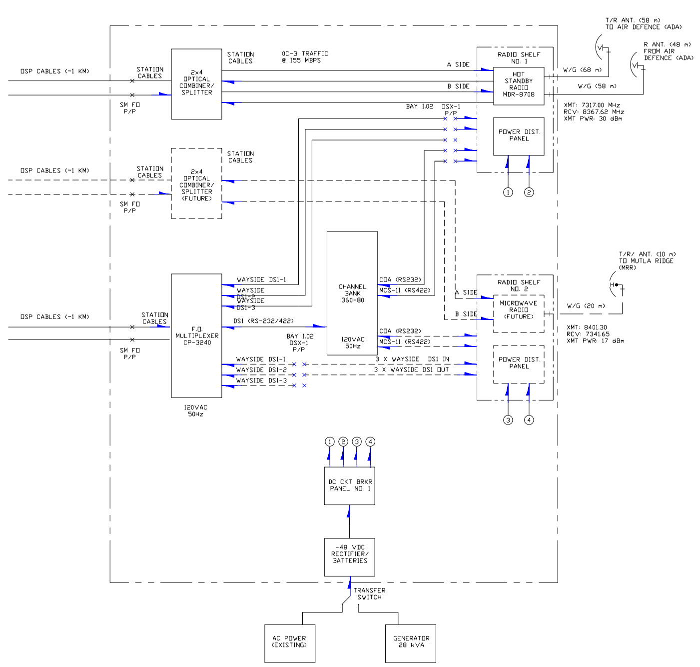

Figure 10. Microwave station block diagram.

FACILITY DESIGN

The microwave system design, field surveys, study of route alternatives, path designs, and the integration of these with the network as a whole; once all of this has been accomplished, the considerable task of designing and building the facilities remains. Site planning will have started during the field surveys with attention to site plans, access roads, site preparations, building design, and station grounding. The detailed facility design phase will encompass the building or shelter, towers, power, environmental control, operational and maintenance subsystems for alarms and orderwire communications, electromagnetic compatibility and a security fence around the site boundary. Throughout the construction of a site, the presence of an experienced onsite engineer who has detailed engineering drawings of all aspects of the installation is essential to ensure a high standard of workmanship.

Buildings and Shelters. The building or shelter size and characteristics are determined in large part by the space required to lay out the equipment in an orderly and logical arrangement which provides adequate access for maintenance and trouble-shooting. Microwave radio buildings typically require both AC and DC power.

Lighting and outlets for test instruments, power tools, etc. use standard AC power, but critical equipment loads typically use DC, usually at -48 volts. In both cases, emergency backup power is supplied by a generator which has a fuel tank.

Shelters have the advantage of modularity, and they can be fitted out with equipment and tested at the factory prior to shipping to site. That is usually easier and faster than to install the equipment onsite. Once the shelter is placed on its concrete pad, final interface and power cable connections are made, then commissioning tests are performed.

Towers. The number of antennas, their sizes and heights from the path design, the waveguide runs, and the area of the site determine the size and type of tower needed. If space on the site is limited, a self-supporting tower would be selected. But if more land is available, a guyed tower is more economical.

For a new tower, a geotechnical engineer must be brought in to collect and analyze core soil samples. His report is the basis for designing a sufficiently strong foundation to support the tower. Tower foundations are designed by registered professional civil or structural engineers as a specialty. They also analyze the proposed antenna and waveguide loads to ensure safety and performance. The foundation for a large tower will sometimes require weeks for the concrete to cure before the tower can be erected, and this lead time should be taken into account in the project schedule. Also the painting and lighting of a tower must be in compliance with the country's aeronautical safety codes.

For the long term, after a tower and its mounted antennas have been put into service, the mechanical stability of the structures should be monitored as part of the maintenance program. Antennas and their supporting tower structure are subjected to dynamic wind loading and, in some cases, seasonal static ice loads. The structural responses are unwanted elastic displacements (twist and sway) and inelastic deformation from the static load, backlash in antenna mounts, slippage in mounting clamps, changes in guy wire tension, foundation settling, and bending of structural members. Not only are these changes undesirable structurally, but they will cause antennas to point away from the alinement direction for the radio path, degrading link performance [12].

Grounding, bonding and shielding of all site facilities and structures, inside and outside, is of paramount importance for personnel safety and equipment protection [13]-[15].

SUMMARY

Microwave line-of-sight propagation is based on the principles of electrodynamics. The two idealizations of free space loss in a uniform medium and the reflection loss from a plane earth are the starting points for propagation analysis. In practice, fading caused by actual terrain, atmospheric and climatic conditions forces the microwave engineer to take a statistical approach to predicting the power loss and distortion of a received signal over time. Despite the complications of radio propagation, a microwave communication system is in some cases more economical and flexible than a cable transmission system.

Performance objectives for a microwave transmission system are derived from the system requirements for the overall network. The three elements of transmission system planning are traffic analysis, provisioning, and network topology. Once the locations of candidate node and repeater sites are known, path profiles and calculations are done to determine what equipment parameters are required to meet a stated availability goal. Field surveys are a practical necessity to verify or correct the accuracy of terrain elevation data, obstructions, and meteorological data.

In working out the microwave route topology, interference and frequency coordination are important considerations. The effects of interference are mutual, thus one must seek to limit the new system's interference to existing systems as much as to shield the new system from external sources of interference. Microwave communications is feasible because of the disciplined coordination of licensed frequency channel assignments. Ultimately the limited bandwidth of those channels means a limit to their information bearing capacity as data rates over other transmission media continue to increase. This trend is opening up the millimeter-wave region of the radio spectrum where numerous point-to-point links can use large bands of spectrum simultaneously in a small geographic area.

Under the impetus of integrated services and their multi-gigabit per second data streams, line-of-sight radio transmission systems appear to be entering a period of transition from the channelized microwave and lower millimeter-wave bands of the present to millimeter-wave bands that are coordinated on the principle of *spatial reuse* [11]. If millimeter-wave radio relay systems turn out to be practical, the major consequences will be, first and foremost, the widespread distribution of high bandwidth integrated services to more subscribers at lower cost. Second, the microwave sites of the present day will be transformed in size, equipment, and infrastructure from large towers and antennas, waveguide, and radios housed in buildings on a fenced-in plot of land to compact integrated antenna and transceiver units, mounted lower to the ground, and using rights-of-way of other industries (rail, pipeline, etc.) for distribution. The goal will remain the same, however: to provide wideband communications services to less densely populated regions or over large distances of rugged terrain for which fiber optic cable would not be a feasible economic alternative.

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BIOGRAPHICAL SKETCH

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